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ANALYSIS OF NON-UNIFORM, SHORT-CRESTED OCEAN WAVES FOR DEPTH DETERMINATION, BASED ON WAVE VELOCITY METHOD, FROM TIMED VERTICAL PHOTOGRAPHS TAKEN OVER CLATSOP SPIT, OREGON

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The theory on which this investigation, the determination of depths from vertical aerial photographs taken over non-uniform short-crested waves. is based, appears in Reference 2. In the foregoing report, the motion of waves whose crest height varies transversely to the direction of travel has been investigated. Such waves are called "short-crested" to distinguish them from waves having long straight crests at right angles to the direction of travel, which are called "long-crested". Since most wind generated waves of appreciable size are short-crested, to some extent, the term short-crested has usually been reserved for waves for which the two associated wavelengths are of the same order of magnitude. It is found that the weakest winds which are capable of raising waves at all, generate long-crested waves. But stronger winds can and do raise short-crested waves. To a first approximation, for which the waveheight to wavelength ratio is small, the surface elevation may be written

$$\eta = a \cos\left(\frac{2\pi}{L}x - \frac{2\pi}{T}t\right)\cos\frac{2\pi}{L'}y$$

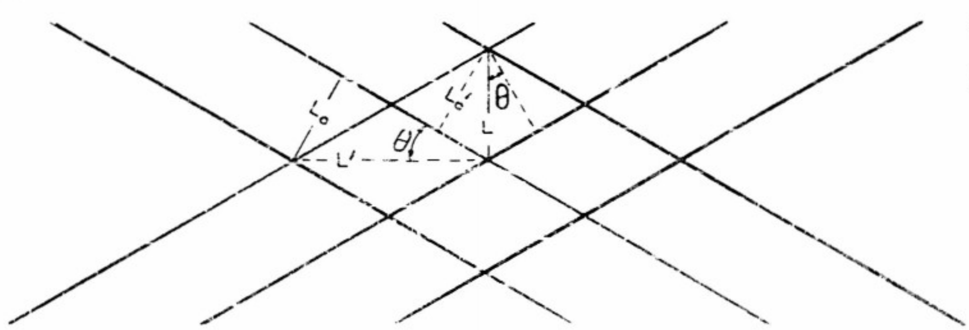
where x is the distance from some fixed line perpendicular to the direction of travel, y is the distance from another fixed line in the direction of travel, L is the wavelength in the direction of travel, L' is the wavelength at right angles to the direction of travel, T is the period and a is the amplitude.

Actually a short-crested wave can be represented as the sum of two long-crested waves traveling at equal and opposite angles to the positive x-direction for

$$\eta = \frac{a}{2}\cos\left(2\pi\left(\frac{x}{L}+\frac{y}{L'}\right) - \frac{2\pi}{T}t\right) + \frac{a}{2}\cos\left(2\pi\left(\frac{x}{L}-\frac{y}{L'}\right) - \frac{2\pi t}{T}\right).$$

The first long-crested component has crests parallel to the line $y = -\frac{L'}{L}x$

while the second has crests parallel to the line $y = \frac{L'}{L}x$. Such a wave is capable of traveling unchanged in form with a velocity determined directly from the velocities of its long-crested components. We denote by L_0, C_0 and T the wavelength, velocity and period of one of the long-crested component waves, and by C and T corresponding quantities for the short-crested wave. Denoting by 2θ the angle between the two lines of crests, we see from the sketch below



that

$$L_0 = L\cos\theta$$
$$= L'\sin\theta.$$

Thus

$$C = \frac{L}{T} = \frac{L_o}{T}\ \frac{1}{\cos\ \theta} = \frac{C_o}{\cos\ \theta}\ .$$

In water of constant depth d the velocity of a long-crested waves is given by

$$C_o^{\,2} = \frac{g\,L_o}{2\,\pi}\ \tanh \frac{2\,\pi\,d}{L_o}\ .$$

Substituting for C_o and L_o in terms of L and L' we find that

$$C^2 = \frac{g\,L}{2\,\pi}\ \frac{1}{\cos\ \theta}\ \tanh \frac{2\ \pi\ d}{L\ \cos\ \theta}$$

$$= \frac{g\,L}{2\,\pi}\ \sqrt{1 + \left(\frac{L}{L'}\right)^2}\ \ \tanh\left(\frac{2\,\pi\ d}{L}\ \sqrt{1 + \left(\frac{L}{L'}\right)^2}\right)\ .$$

This equation can be rearranged to give

$C = \frac{g\,T}{2\,\pi}\ D\ \tanh \frac{2\,\pi\,d}{L}\ D$ where T is the wave period and $D = \sqrt{1 + \left(\frac{L}{L'}\right)^2}$.

When a short-crested wave moves shoreward each component wave refracts so as to become parallel to the shore. If the short-crested wave moves at right angles to the shore line the length L' remains unchanged while L decreases. The result is an apparent change to a long-crested wave form.

Timed vertical aerial photographs of surf areas in the vicinities of Monterey and Oceanside, California, and of Clatsop Spit, Oregon, were examined. Only those taken at Clatsop Spit exhibited a short-crested, non-uniform wave pattern; the other two areas indicated long-crested uniform waves. Out of a total of seven sorties flown over Clatsop Spit, five were analyzed for wave velocity and for depths. These were Sorties number 49A (4-9) May 6, 1950; 49A (13-17) May 6, 1950; 53B May 10, 1950; 55A May 15, 1950; 59A (10-14) May 18, 1950 and 59A (22-26) May 18, 1950. (See References 1 and 5).

For determining depths between breaker zone and the shore, the equation $C^2 = g\,d$ was used.

Three methods were followed in computing depths outside the breaker zone. First was a modification of J.W. Johnson's method, described in Reference 3. The second method was an arithmetical solution for the instantaneous velocity of the wave crests by tabulating distances vs. times and using third differences, and computing each individual wave length at a point--the point being the position of the crest on the range line. The wave length at the point was determined by interpolation rather than by an averaging process. In this method, the periods were computed directly from the velocities and wave lengths. In the third method, average velocities and average periods were determined as in J.W. Johnson's method, but wave lengths at the crest positions were determined by interpolation as in the second method.

Since the quantity L/L' is used in the velocity equation when dealing with short-crested waves, the crest length must be measured on the photograph-

In this study, the crest pattern was marked on the photographs using a grease marking pencil until a major portion of the photo area was delineated. The pattern resolves into a diamond shape, fairly uniform over the entire area. One diagonal is the value L, the other is L'. The measurement of the diagonals is not critical since a large change in the ratio produces but a small change in quantity D. The diagonals were measured over the area of the range lines, and an average value was adopted for different portions of the ranges. Through the five sorties, the values of L/L' varied only from 0.20 to 0.33, causing a variation in D of from 1.02 to 1.05. Although values of L/L' close to unity are found in deeper water, refraction tends to decrease this ratio markedly as waves approach shallow water. One is lead to the conclusion that in the shallow depths of interest for amphibious landings the effect of the wave length L' is negligibly small and one can apply the long-crested theory with little error in this respect. Side and Panton (Reference 6) found that the transformation from short- to long-crested waves takes place when d/L is about 1/13. They assume that waves are long-crested when the crest length is five times the wave length.

Tables 1 through 4 are included to show the mechanics of tabulation and of computation. The determination of individual scales for each photograph is not included since it involved simply the ratio of the measured distance on the photograph to the known ground distance between the tops of two towers, and reducing this ratio to a sea level scale. It may be well to point out that these individual scales are subject to errors of an erratic nature due to tilt.

Table 1 is a consolidation of the tabulated distances out to wave crests scaled on the photographs 22 through 26 of Sortie 59A.

Table 2 shows the method of determining instantaneous velocities of the wave crests at a particular instant of time. In a five-photo sortie, the instant is the time of exposure of the third photograph. Distances out to each crest are tabulated alongside the times of exposure. The algebraic differences between distances are tabulated in the next column on alternate rows. These are the first differences designated Δ'_0. The algebraic differences of the Δ'_0's are tabulated in the following column on alternate rows. These are the second differences designated Δ''_0. The algebraic differences of the Δ''_0's are the third differences designated Δ'''_0, and are listed as shown. The quantities in parentheses are the first and third difference columns and on line with the times are the mean of the differences above and below the numbers in parentheses. In the first difference column, they are designated $\Delta'_{1/2}$; in the third difference column they are designated $\Delta'''_{1/2}$. The equation for velocity then is $C = \frac{\Delta'_{1/2}}{\Delta t} - \frac{\Delta'''_{1/2}}{6 \Delta t}$. Where distances to crests are not shown, the velocities are actually obtained from first differences only.

The interpolation for wave lengths at crest positions together with the calculations for depth are shown in Table 3. Data from the tables in Reference 4 were used to determine the quantity dD/L, having determined the quantity $\tanh \frac{2\pi dD}{L} = \frac{2\pi C}{DgT}$. The value of d/L in the table opposite the value of $\tanh \frac{2\pi dD}{L}$ (listed as $\tanh \frac{2\pi d}{L}$) is multiplied by L/D to obtain d which is then reduced to MLLW by the tide correction.

Table 4 includes the tabulation for depths inside the breaker zone B and for depths outside the breaker zone by J.W. Johnson's method. The only variation from Johnson's method is the use of the term D which applies to short-crested systems.

The time-distance diagram (Figure 1) is included to show how the average velocities and periods for Table 4 are determined. The period of 10.4 seconds was obtained by averaging over three ranges, whereas the lines representing periods are shown for range 0+00 only, and the average of these lines will not be 10.4 seconds.

None of the profiles plotted from the results are satisfactory. (See Figures 2,3,5 and 6) Several of the points are off as much as 100% of the sounded depth. Only a few of the profiles suggest the actual shape of the profile. The methods applied do not seem to be sensitive to bottom irregularities except in a few cases, and these few instances may be purely accidental. Only the general trend of the beach gradient is reliable.

The sorties which showed the greatest non-uniformity of scale were analyzed again using an average scale to see whether perhaps the variation in scale was due to tilt, rather than to variable flying height. As indicated in the profiles in the appendix, this did nothing to improve the profiles, rather it increased the errors in general.

Sorties 48A, 49A and 52B, when averaged out, gave a very regular profile, good in portions, but much in error out in the deeper water (see Figure 4).

In general, the computed depths were too small except for those determined from sortie 55A. This particular sortie exhibited relatively short-period waves, the order of 10 seconds. However, sortie 59A showed about the same period, and yet on studying the resulting profiles, it is seen that those from this sortie are better than any of the others. The photographs in all seven groups were generally about of the same photographic quality, that is to say, the wave crests stood out equally well, the tone was the same, and the scale variations were of the same magnitude. It is difficult to say where the difference lies which would cause such variations in the computed depths. All seven groups would logically be subject to the same experimental errors. Each group, of course, is subject to the errors in taking the soundings. As pointed out in References 1 and 5, there was a definite daily change in profiles which was particularly pronounced following periods of high waves (see Figure 4). The errors in computed depths, however, were much greater than would be caused by errors in soundings and changes in profiles in the elapsed time between soundings and photography.

The Johnson method is very definitely the most straightforward method of making measurements and reducing the data to actual profiles. The other two methods, namely interpolating to find velocities and wave lengths arithmetically, and interpolating to find wave lengths using Johnson's time-distance diagram for velocity, do not appear to add any more accuracy to the method. They simply take more time.

We are faced with the situation where, in applying wave theory of regular short- or long-crested waves to waves of great irregularity, we do not get a satisfactory answer. Although it would be physically possible to obtain photographs which give the three-dimensional representation of the sea surface at the same time that we obtain photography to measure wave advance, practically, the labor involved in taking the photography and in measuring and reducing the data to actual depths would be prohibitive. On the other hand, this is the type of data that would be needed to make any just analysis of non-uniform wave systems. A practical solution to the problem is not adequate. The solution must be rigorous. If a practical and expedient approach is to be used, then the inadequacy of the solution must be recognized and appreciated, admitting of errors and inconsistancies.

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Clatsop Spit, Oregon
Sortie 59A(22-26)
18 May 1950 3:50 PM PDST
Range 0 + 00

	Scaled distance from base (ft)					Distance from base (ft)				
Wave No.	Photo22 1:5746	Photo23 1:5737	Photo24 1:5723	Photo25 1:5709	Photo26 1:5717	Photo22 6:5s	Photo23 10:5s	Photo24 14:5s	Photo25 18:6s	Photo26 22:6s
1	.0460	.0446	.0443	-	-	264	256	254	-	-
2	.0548	.0502	.0490	-	-	315	288	280	-	-
4	.0701	.0646	-	-	-	403	371	-	-	-
5	.0820	.0676	.0602	.0574	-	471	389	345	328	-
6	.0895	.0762	.0677	.0593	.0542	514	437	387	339	310
8	.1057	.0990	.0900	.0803	.0710	607	568	515	458	406
9	.1337	.1201	.1100	.1008	.0910	768	689	630	575	520
10	.1518	.1430	.1336	-	-	872	820	765	-	-
11	.1676	.1570	.1482	.1360	.1239	963	901	848	776	708
12	-	-	.1704	-	-	-	-	975	-	-
13	.2107	.1962	.1835	.1695	.1546	1211	1126	1050	966	884
14	.2281	-	.2004	.1849	.1730	1311	-	1147	1056	989
15	.2512	.2343	.2195	.2067	.1914	1443	1544	1256	1180	1094
16	.2787	.2600	.2410	.2262	.2145	1601	1492	1379	1291	1226
18	.3338	.3114	.2920	.2756	.2587	1918	1787	1671	1573	1479
19	.3883	.3679	.3490	.3340	.3130	2231	2111	1997	1907	1789
20	.4383	.4172	.4016	.3832	.3641	2518	2393	2298	2188	2082
21	.4774	.4569	.4395	.4195	.4046	2743	2621	2515	2395	2314

Table 1. Tabulated scaled distances and computed distances from baseline.

Clatsop Spit, Oregon
Sortie 59A(22-26)
18 May, 1950 3:50 PM PDST
Range 0 + 00

Δt		t	Dist.	Δ'_c	Δ''_o	Δ'''_o	C	Dist.	Δ'_o	Δ''_o	Δ'''_o	C
			Wave 9					**Wave 10**				
		6.5	768					872				
	4.0			-79					-52			
4.0		10.5	689	(-69)	+20			820	(-54)	-3		
	4.0			-59		-16			-55		+3	
4.05		14.5	630	(-57)	+4	(-10)	13.6	765	(-55)	0	(+2)	13.6
	4.1			-55		-4			-55		0	
4.05		18.6	575	(-55)	0				(-55)	0		
	4.0			-55					-55			
		22.6	520									
			Wave 11					**Wave 13**				
		6.5	963					1211				
	4.0			-62					-85			
4.0		10.5	901	(-58)	+9			1126	(-81)	+9		
	4.0			-53		-28			-76		-15	
4.05		14.5	848	(-63)	-19	(-3)	15.3	1050	(-79)	-6	(-6)	19.3
	4.1			-72		+23			-82		+4	
4.05		18.6	776	(-70)	+4			968	(-83)	-2		
	4.0			-68					-84			
		22.6	708					884				
			Wave 14					**Wave 15**				
		6.5	1311					1443				
	4.0			-82					-99			
4.0		10.5	(1229)	(-82)	0			1344	(-94)	+11		
	4.0			-82		-9			-88		+1	
4.05		14.5	1147	(-87)	-9	(+12)	22.0	1256	(-82)	+12	(-11)	19.8
	4.1			-91		+33			-76		-22	
4.05		18.6	1056	(-79)	+24			1180	(-81)	-10		
	4.0			-67					-86			
		22.6	989					1094				

Table 2. Determining instantaneous velocities by third differences.

Clatsop Spit, Oregon
Sortie 59A (22-26)
18 May, 1950 3:50 PM PDST
Range 0 + 00

Wave No.	Dist. from Base (ft)	L at* ½point (ft.)	Dist. to* ½point (ft.)	L at* Crest (ft.)	C (ft/sec)	T(sec)	D	tanh 2 π dD / L	D / L	d(ft)	d corr. to MLLW (ft)
8	515										
		115	573								
9	630			124	13.6	9.1	1.02	.286	.0468	5.7	0.1
		135	698								
10	765			103	13.6	7.6	1.02	.342	.0567	5.7	0.1
		83	807								
11	848			100	15.3	6.5	1.02	.449	.0769	7.5	1.9
		127	912								
12	975			-							
		75	1013								
13	1050			84	19.3	4.4	1.02	.837	.1925	15.8	10.2
		97	1099								
14	1147			103	22.0	4.7	1.02	.894	.2293	23.2	17.6
		109	1202								
15	1256			116	19.8	5.9	1.02	.640	.1207	13.7	8.1
		123	1318								
16	1379			173	25.4	6.6	1.02	.734	.1492	25.4	19.8
		292	1525								
18	1671			308	26.2	11.7	1.02	.427	.0726	21.9	16.3
		326	1834								
19	1997			313	24.4	12.8	1.02	.364	.0608	18.7	13.1
		301	2148								
20	2298			252	25.0	10.1	1.02	.472	.0816	20.2	14.6
		217	2407								
21	2515										

* Interpolation to determine wave length at crest position

Table 3. Depth determination by instantaneous velocities and interpolated wave length.

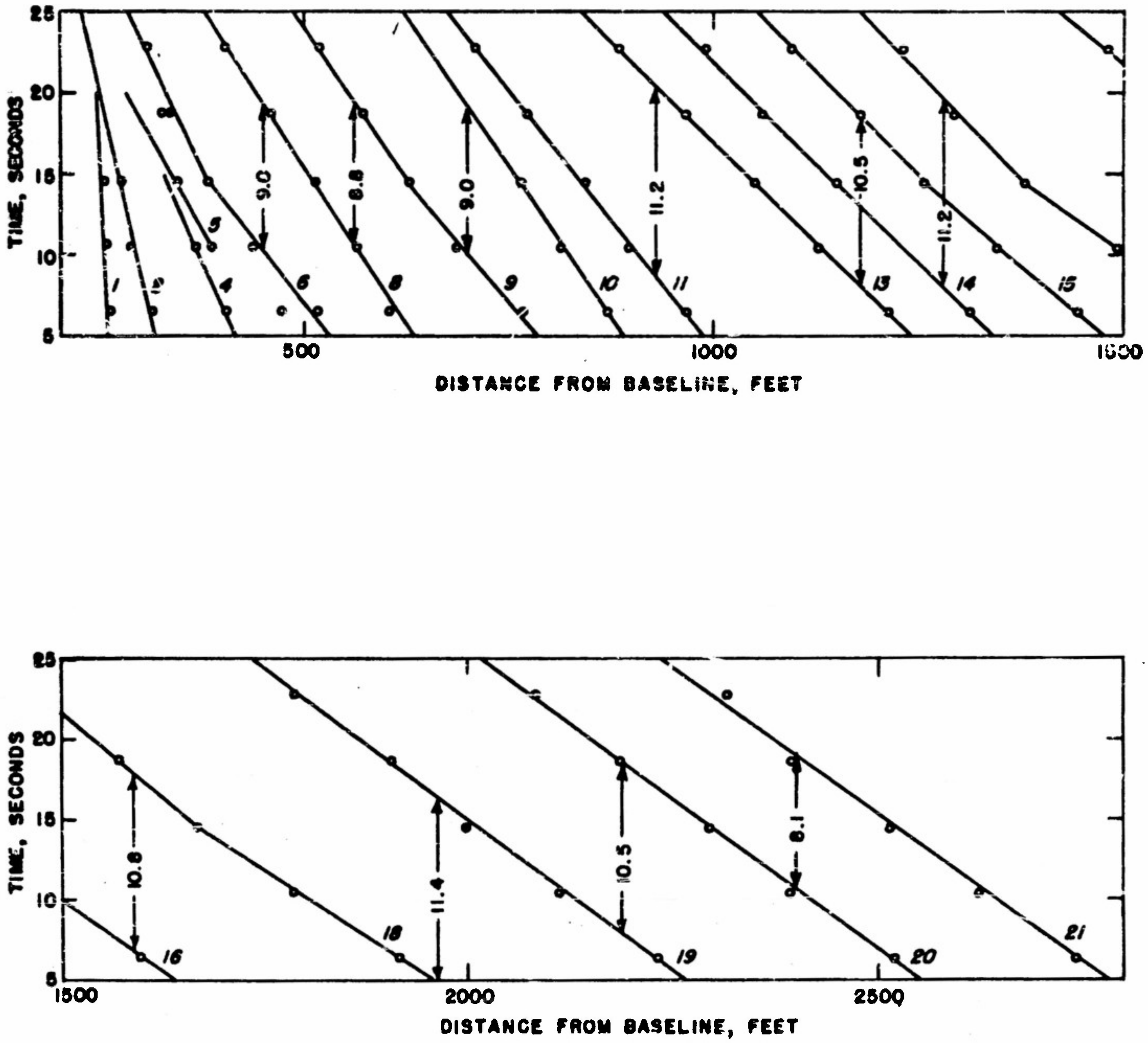
T = 10.4 sec.
C_o= 53.2 ft/sec
L_o= 553'
D = 1.02

Clatsop Spit
Sortie 59A(22-26)
18 May 1950 3:50 PM PST
Range 0+00
Tide Stage 5.6'

Wave Number	Dist* from Base (ft.)	C* (ft/sec)	d (ft)	d corr. to MLLW (ft)		
1	260	0.9	0	-5.6		
2	300	4.5	0.6	-5.0		
4	390	8.6	2.3	-3.3		
5	370	11.0	3.8	-1.8	Based on $C^2 = gd$	
6	340	9.2	2.6	-3.0		
6	450	15.4	7.4	1.8		
8	510	12.8	5.1	-0.5		
			C/C_oD	d D/L_o	d(ft)	d corr. to MLLW (ft)
9	580	13.4	.247	.0099	5.4	-0.2
9	700	17.2	.317	.0165	8.9	3.3
10	820	13.5	.249	.0101	5.5	-0.1
11	840	15.6	.288	.0136	7.4	1.8
13	1050	20.2	.372	.0231	12.5	6.9
14	1150	20.2	.372	.0231	12.5	6.9
15	1180	20.0	.369	.0228	12.4	6.8
15	1350	23.4	.431	.0318	17.2	11.6
16	1300	19.0	.350	.0204	11.1	5.5
16	1490	27.6	.508	.0452	24.7	19.1
18	1580	23.6	.435	.0323	17.5	11.9
18	1800	30.8	.568	.0582	31.5	25.9
19	2010	26.7	.492	.0422	22.9	17.3
20	2310	26.9	.495	.0428	23.2	17.6
21	2520	27.4	.505	.0448	24.3	18.8

* Obtained from time-distance diagram

Table 4. Depth determination - Johnson method



CLATSOP SPIT, OREGON

18 May 1950

Sortie 59A (22-26)

Range 0+00

T = 10.4 secs.

C_o = 53.2 ft./sec.

L_o = 553 ft.

HYD-6691

FIGURE 1

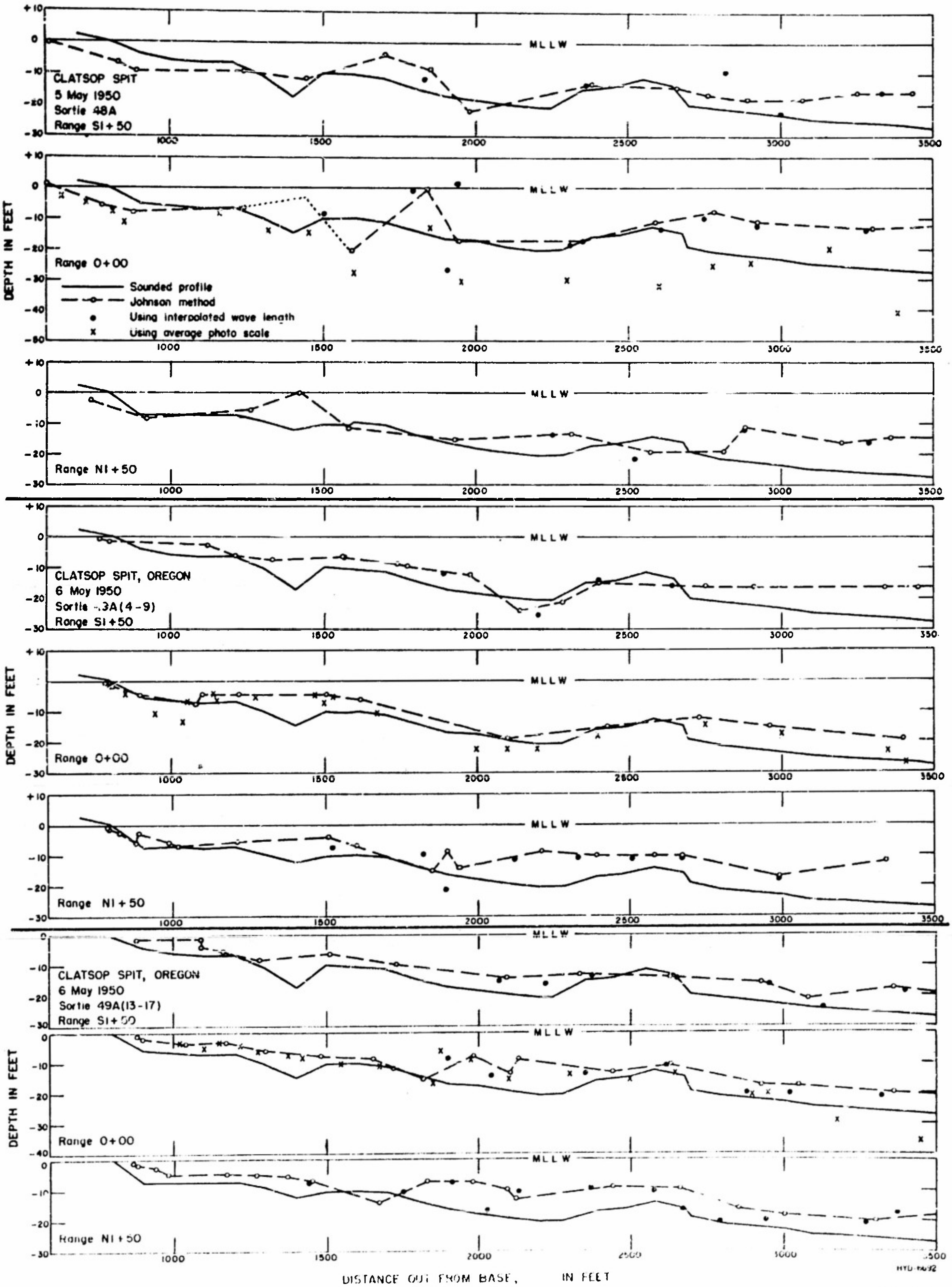

CLATSOP SPIT
5 May 1950
Sortie 48A
Range S1+50
MLLW
Range 0+00
Sounded profile
Johnson method
Using interpolated wave length
Using average photo scale
Range N1+50
CLATSOP SPIT, OREGON
6 May 1950
Sortie 43A(4-9)
Range S1+50
Range 0+00
Range N1+50
CLATSOP SPIT, OREGON
6 May 1950
Sortie 49A(13-17)
Range S1+50
Range 0+00
Range N1+50
DEPTH IN FEET
DISTANCE OUT FROM BASE, IN FEET
HYD-6692

FIGURE 2

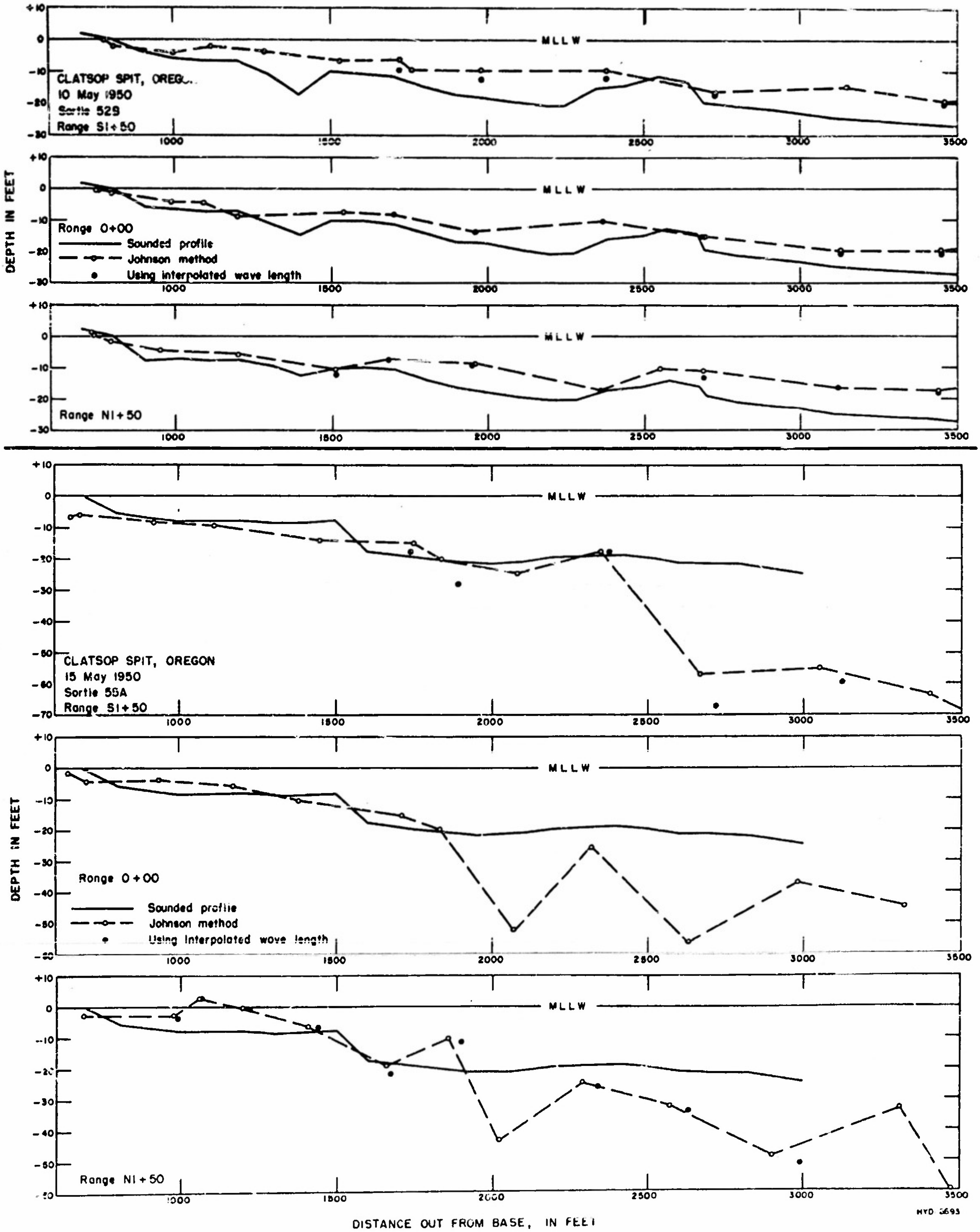
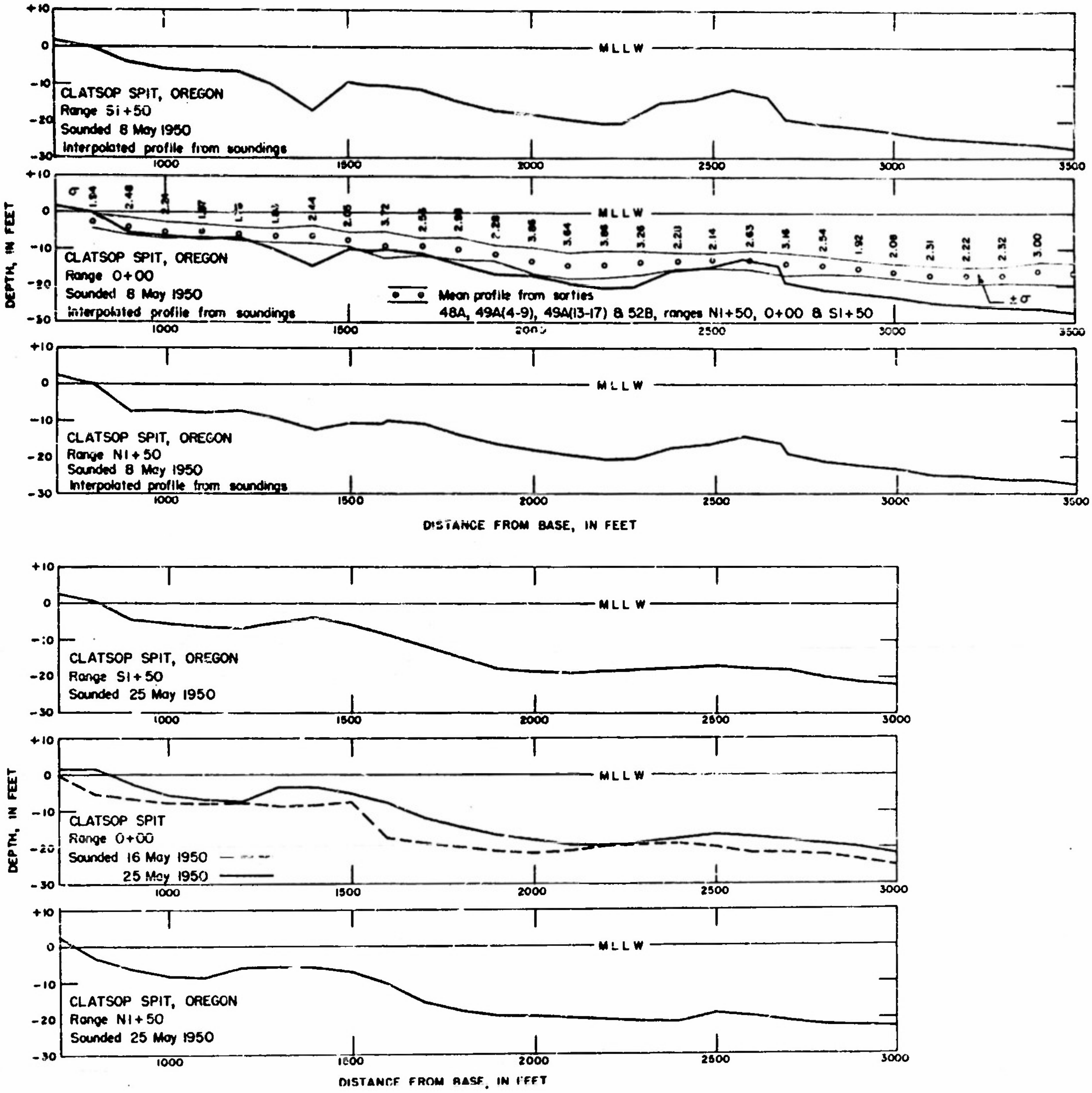

CLATSOP SPIT, OREGON
10 May 1950
Sortie 52B
Range S1+50
Range 0+00
Range N1+50
MLLW
Sounded profile
Johnson method
Using interpolated wave length
DEPTH IN FEET
CLATSOP SPIT, OREGON
15 May 1950
Sortie 55A
Range S1+50
Range 0+00
Range N1+50
DISTANCE OUT FROM BASE, IN FEET
HYD 5693

FIGURE 3



HYD-6694

FIGURE 4

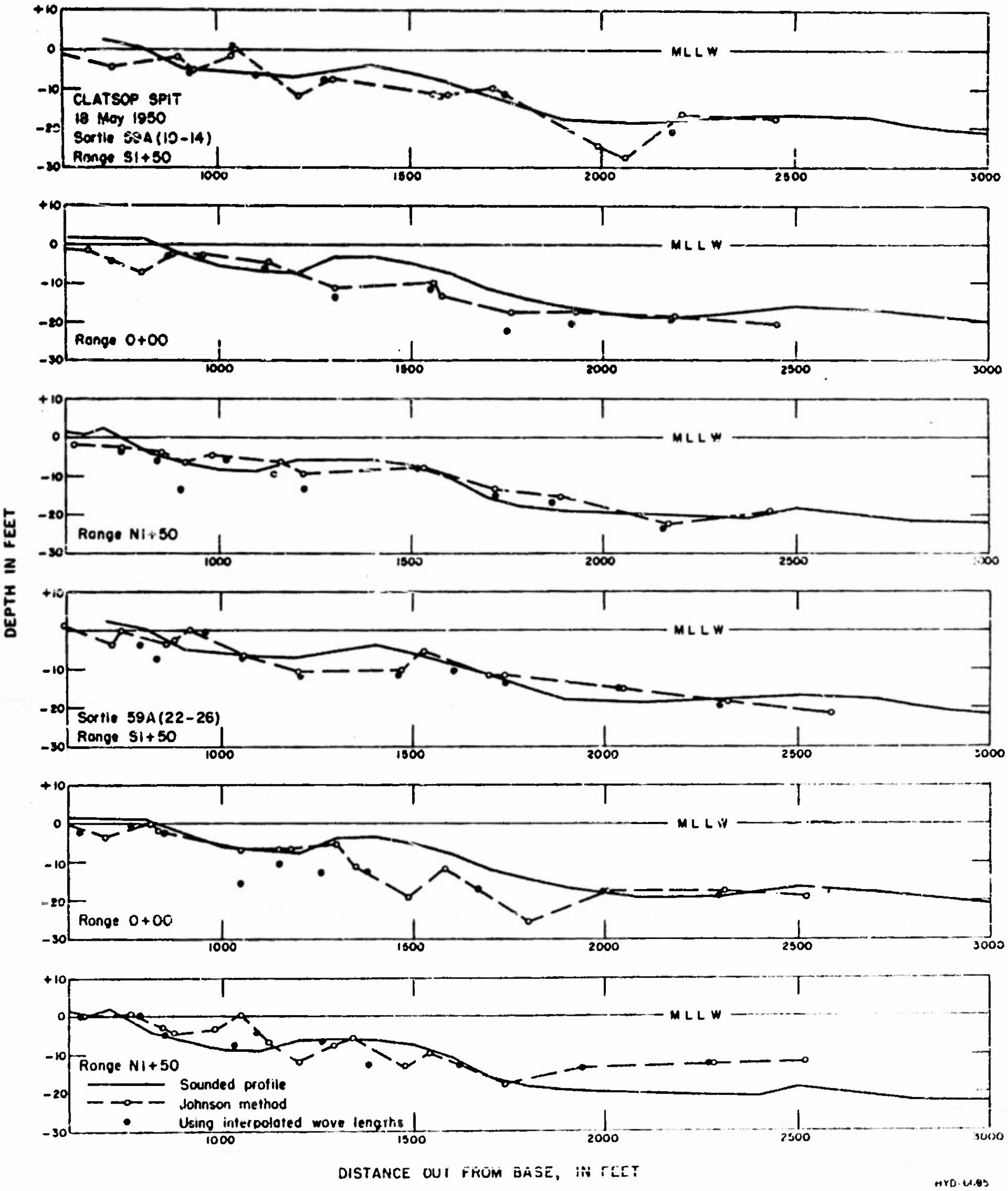

CLATSOP SPIT
18 May 1950
Sortie 59A (10-14)
Range S1+50
Range 0+00
Range N1+50
Sortie 59A (22-26)
Range S1+50
Range 0+00
Range N1+50
MLLW
Sounded profile
Johnson method
Using interpolated wave lengths
DEPTH IN FEET
DISTANCE OUT FROM BASE, IN FEET

FIGURE 6

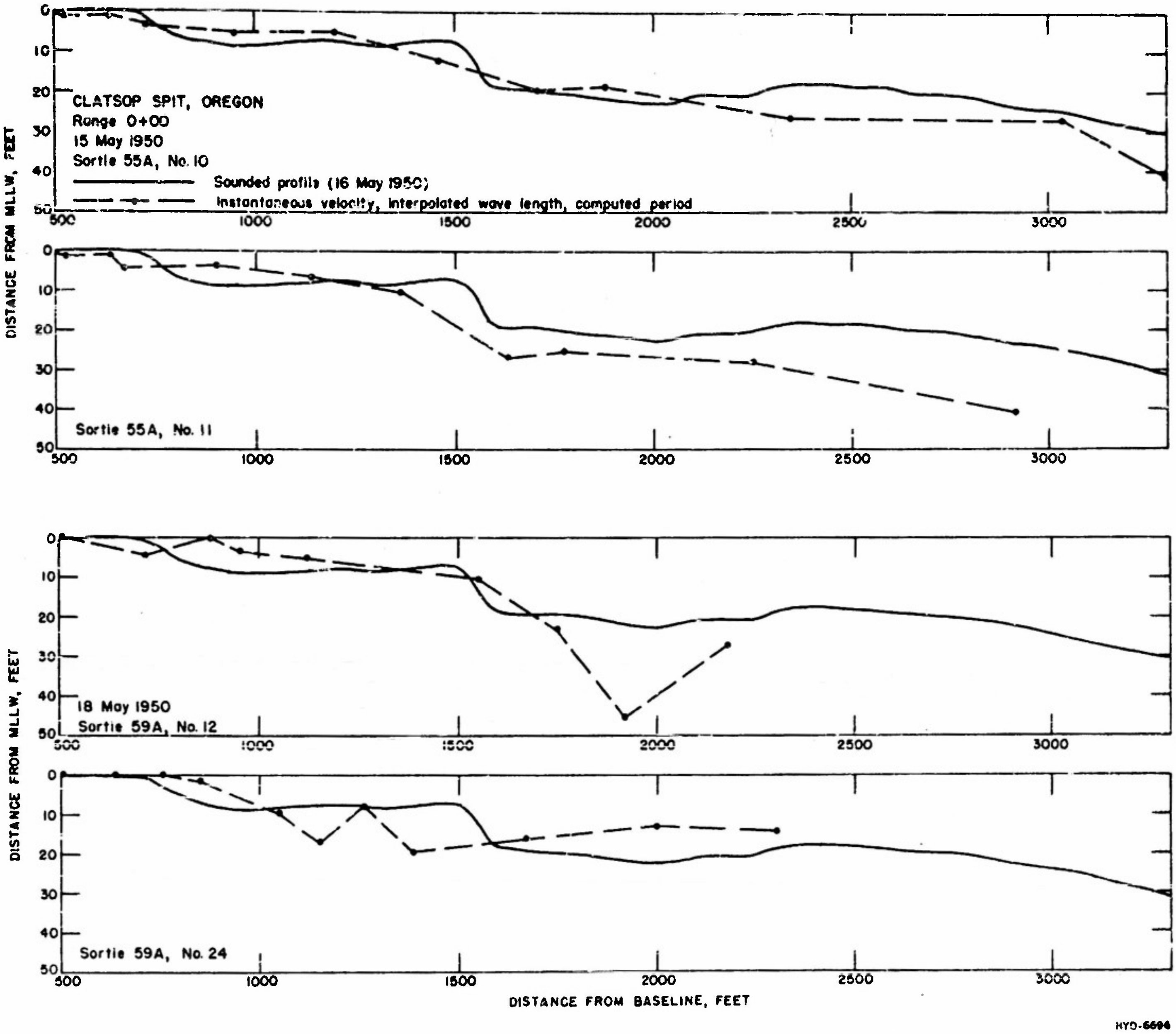

CLATSOP SPIT, OREGON
Range 0+00
15 May 1950
Sortie 55A, No. 10
Sounded profile (16 May 1950)
Instantaneous velocity, interpolated wave length, computed period
Sortie 55A, No. 11
18 May 1950
Sortie 59A, No. 12
Sortie 59A, No. 24
DISTANCE FROM MLLW, FEET
DISTANCE FROM BASELINE, FEET
HYD-6694

FIGURE 6

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